# The Rising Cost of Climate Change: Evidence from the Bond Market

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# Social discounting and the economics of climate change

- GHG emissions cause long-lasting damages far into the future, therefore *social discounting* plays central role for cost-benefit analysis
  - Compare near-term costs of climate change mitigation to present value of reduced future damages (social cost of carbon, SCC)
- *Level* of social discount rate (SDR) has enormous impact on present values
- *Term structure* of SDRs is needed for different horizons
- Vast literature on social discounting and climate change.
  - Reviews by Arrow et al. (1996, 2014), Gollier (2013), Gollier and Hammitt (2014)
- Much disagreement remains about appropriate SDRs for assessing climate change damages and measuring SCC

# Two approaches to social discounting

## Prescriptive approach: What SDR is optimal/fair/ethical?

- *Normative analysis* based on social welfare, theory (Ramsey rule), judgments
- Example: Stern Review (2007) used a normative SDR $\approx 1.4\%$

## Descriptive approach: What are observed real returns in financial markets?

- *Positive analysis*: financial returns reflect preferences, intertemporal trade-offs
- Nordhaus (2007): "normatively acceptable real interest rates prescribed by philosophers, economists, or the British government are irrelevant to determining the appropriate discount rate"—instead use "real real interest rate"
- Example: Nordhaus generally uses a real return of 4%.

Descriptive SDRs tend to be *significantly higher* than prescriptive SDRs.

- 2 percentage points higher in survey of experts (Drupp et al., 2018).

# This paper: new descriptive approach based on macro-finance

- Show that equilibrium/steady-state real interest rate, $r_t^*$, anchors term structure of SDRs (level factor)
  - Consensus in macro-finance literature: pronounced decline in $r_t^*$
- Incorporate $r_t^*$ into empirical time series model for risk-free SDRs
  - Shifting-endpoint model for Treasury yields to estimate $r_t^*$ and infer unobservable long-run SDRs
  - Estimated decline in $r_t^*$ about 1-2 p.p. in recent decades
  - Lower $r_t^*$ implies substantial *downward shift* in term structure of SDRs
- Social cost of carbon at least doubles
- Bridging the gap: new descriptive SDRs aligned with low normative SDRs
- Our results strengthen the case for immediate, strong mitigation policy.

# Related literature

- Macro-finance theory and estimates of $r_t^*$
  - Laubach and Williams (2016), Caballero et al. (2017), Del Negro et al. (2017), Christensen and Rudebusch (2019), Bauer and Rudebusch (2020), and others
- Descriptive/empirical SDRs
  - Newell and Pizer (2003), Groom et al. (2007), Gollier et al. (2008), Hepburn et al. (2009), Freeman et al. (2015), Newell, Pizer, Prest (2020), and others
  - "Econometric expected net present value" approach (Freeman and Groom, 2016)
  - Generally assume constant long-run mean $r^*$

# Our focus on risk-free SDRs

- Risk-free SDRs appropriate for discounting:
  - Certain future payoffs
  - Uncertain but riskless payoffs—no systematic risk, i.e., no correlation with marginal utility/wealth/growth
  - Certainty-equivalent payoffs—expected payoffs that have been adjusted to account for risk characteristics ("risk-neutral" expectations)
- Risk-adjusted SDRs problematic
  - *Climate beta* (correlation of future damages with marginal utility) unknown, estimates range from unity (Dietz, Gollier, Kessler, 2017) to negative (Giglio et al. , 2018; Daniel, Litterman, Wagner, 2019; Lemoine, 2020)
- Risk-free SDRs are an important benchmark in social discounting, required as first step for calculation of risk-adjusted SDRs

# The anchor for all social discount rates

Define $r_t^*$ as the equilibrium/long-run level of real short rate, $r_t$:

$$r_t^* = \lim_{h \to \infty} E_t r_{t+h}.$$

$r_t^*$ determines the *level of the term structure* of discount rates:

$$\boxed{y_t^{(n)} = r_t^* + \frac{1}{n} \sum_{j=0}^{n-1} E_t \tilde{r}_{t+j} + z_t^{(n)}}$$

$\tilde{r}_t = r_t - r_t^*$ cyclical component of short rate, $z_t^{(n)}$ negative convexity term

- *All* SDRs move one-for-one with $r_t^*$.
- Short-run SDRs are affected by current rates.
- Long-run SDRs are lowered by convexity (Weitzman effect).

# Estimates show $r_t^*$ has declined in recent decades

| Source of estimate | 1990s | 2010s | Change |
|---|---|---|---|
| Del Negro et al. (2017) | 2.3 | 1.1 | -1.2 |
| Johannsen and Mertens (2016) | 1.4 | 0.7 | -0.7 |
| Laubach and Williams (2016) | 2.8 | 0.3 | -2.5 |
| Kiley (2015) | 1.6 | 0.7 | -0.9 |
| Christensen and Rudebusch (2019) | 2.1 | 0.6 | -1.5 |
| UC model, 1y rate | 1.7 | 0.7 | -0.9 |
| Mean | 2.0 | 0.7 | -1.3 |

Estimates of $r_t^*$, decadal averages. Christensen-Rudebusch estimate, based on TIPS yields, starts in 1998.

▸ Figure with r* estimates ▸ Updated Christensen-Rudebusch estimate

# Time series model for SDR with long-run trend

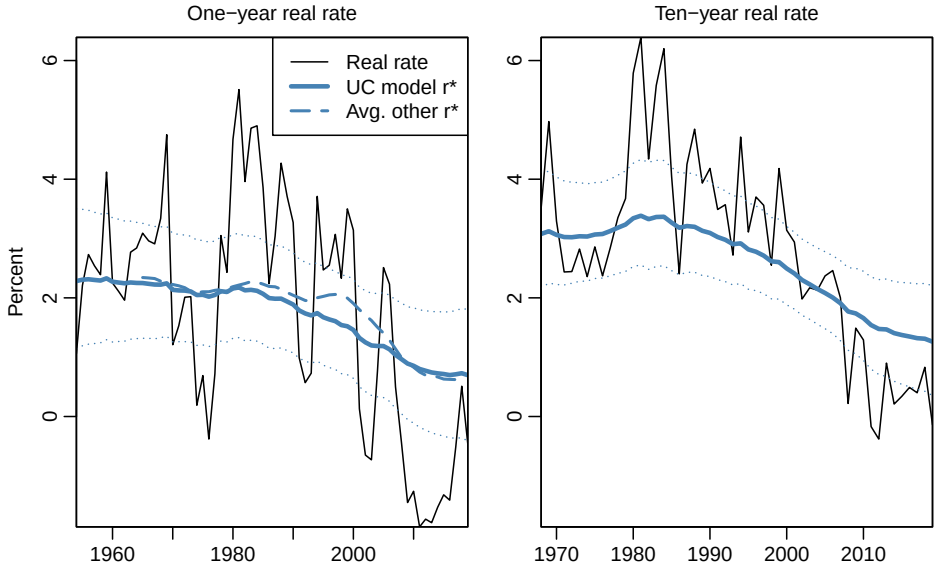
Unobserved-components (UC) model:

$$
\begin{aligned}
r_t &= r_t^* + \tilde{r}_t \\
r_t^* &= r_{t-1}^* + u_t, \qquad & u_t &\sim N(0, \sigma_u^2) \\
\tilde{r}_t &= \phi \tilde{r}_{t-1} + v_t, \qquad & u_t &\sim N(0, \sigma_v^2)
\end{aligned}
$$

- Use annual data on one-year or ten-year real rate proxy $r_t$
  - Difference between Treasury yield and survey-based inflation expectations
- Bayesian estimation using MCMC sampler
  - Tight prior on $\sigma_u^2$ to avoid overly volatile $r_t^*$. (Other priors uninformative.)

*Model provides new estimates of $r_t^*$ and of term structure of risk-free SDRs, based on time series of real interest rate*

# New estimates of equilibrium real rate $r_t^*$



# Estimates of $r_t^*$ declined substantially for all of our models

| | One-year rate | | | Ten-year rate | | |
|---|---|---|---|---|---|---|
| Model | 1990 | 2019 | Change | 1990 | 2019 | Change |
| UC model | 1.9 | 0.7 | -1.2 | 3.1 | 1.3 | -1.8 |
| AR model, break | 2.8 | 0.5 | -2.2 | 3.9 | 1.9 | -1.9 |
| AR model, learning | 2.8 | 1.3 | -1.5 | 3.9 | 2.4 | -1.5 |

Simple AR(3) models that extend Newell and Pizer (2003) to shifting long-mean:

- Structural break in mean in 1990
- Learning about mean using EWMA (following Piazzesi and Schneider, 2007, etc.),

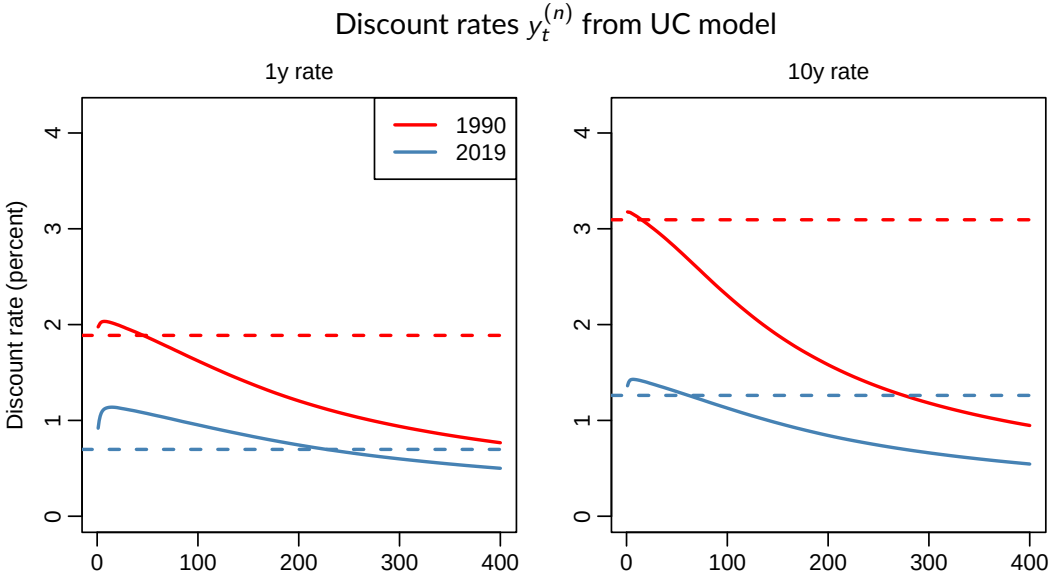
$$r_t^* = \left( \sum_{j=0}^{t} \alpha^j \right)^{-1} \sum_{j=0}^{t} \alpha^j r_t, \quad \alpha = 0.98$$

# Calculating the implied term structure of SDRs

- Calculate model-implied term structure at $t = 1990$ and $t = 2019$ to quantify shift in SDRs due to lower $r_t^*$
- Use expectations hypothesis to obtain SDRs from short rate dynamics
- Simulation approach to solve for bond prices/long rates:
  1. Draw from parameters and $r_t^*$
  2. Simulate 50,000 paths of state variables
  3. Calculate effective real short rate using *shadow rate* specification to rule out negative SDRs: $r_t = \max(0, r_t^* + \tilde{r}_t)$
  4. Calculate term structure of SDRs:

$$y_t^{(n)} = -\frac{1}{n} \log E_t \left[ \exp \left( -\sum_{j=0}^{n-1} r_{t+j} \right) \right]$$

# Term structure of SDRs has shifted down



# The Social Cost of Carbon (SCC)

SCC is present value of future damages, $MD_{t+n}$, from one additional ton of $CO_2$:

$$SCC_t = \sum_{n=0}^{\infty} \exp\left(-n \cdot y_t^{(n)}\right) E_t(MD_{t+n})$$

Two ingredients required to calculate SCC:

1. **Term structure of discount rates** $y_t^{(n)}$
   - Use model-based term structures from 1990 and 2019 to assess how lower $r_t^*$ affects SCC

2. **Future marginal damages** $MD_{t+n}$
   - Take as given: use estimates from Integrated Assessment Models (IAMs)
   - Updated DICE models that account for recent advances in climate science

# Our lower empirical SDRs boost social cost of carbon

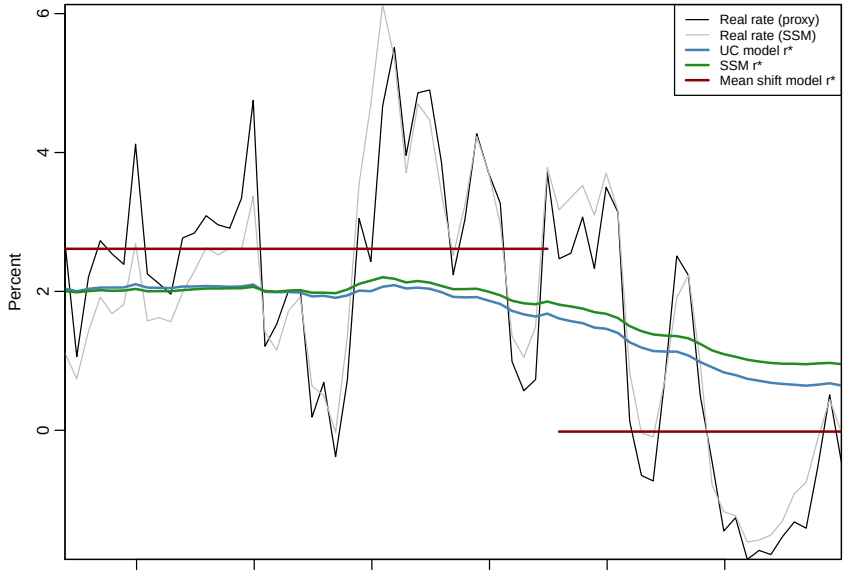
Estimates of 2015 SCC (constant $ per metric ton of $CO_2$)

| Model | Change in $r_t^*$ | 1990 | 2019 | % Change |
|---|---|---|---|---|
| *DICE model of Hänsel et al. (2020)* | | | | |
| UC model, 1y rate | -1.2 | 218.8 | 396.7 | 81% |
| UC model, 10y rate | -1.8 | 127.5 | 340.4 | 167% |
| AR model, break, 1y rate | -2.2 | 107.8 | 422.4 | 292% |
| AR model, break, 10y rate | -1.9 | 64.2 | 188.1 | 193% |
| AR model, learning, 1y rate | -1.5 | 101.2 | 260.4 | 157% |
| AR model, learning, 10y rate | -1.5 | 58.9 | 137.9 | 134% |
| *DICE model of Dietz et al. (2020)* | | | | |
| UC model, 1y rate | -1.2 | 387.6 | 963.1 | 149% |
| UC model, 10y rate | -1.8 | 193.8 | 800.7 | 313% |
| AR model, break, 1y rate | -2.2 | 61.3 | 886.0 | 1346% |
| AR model, break, 10y rate | -1.9 | 32.4 | 175.7 | 443% |
| AR model, learning, 1y rate | -1.5 | 54.9 | 300.5 | 447% |
| AR model, learning, 10y rate | -1.5 | 26.3 | 101.1 | 284% |

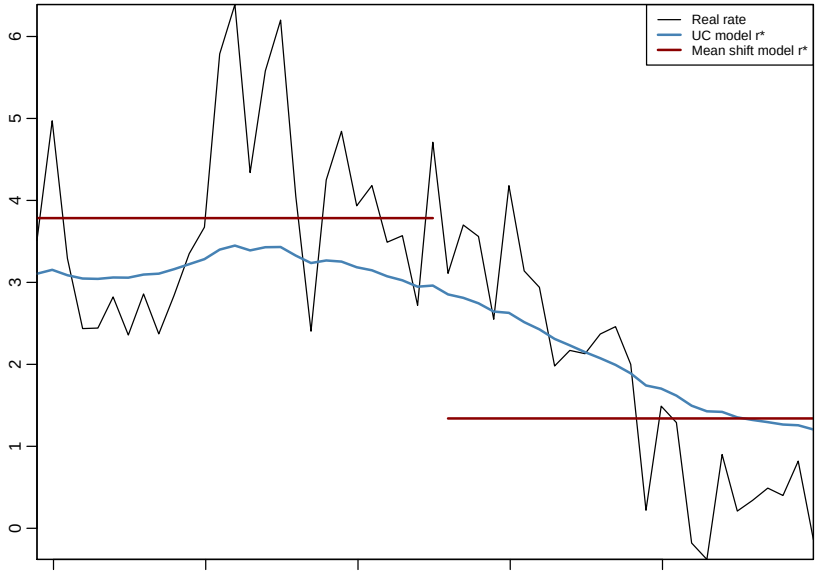
# Conclusion and Outlook

- Macro-finance shifts important for economics of climate change
- Secular decline in $r_t^*$ lowers all discount rates and substantially boosts social cost of carbon
  - Lower level and declining term structure of SDRs important consideration for SCC review of Biden administration
- Previously, SDRs from descriptive approach (market rates) significantly higher than from prescriptive approach (normative judgement). Our results bring both approachs into close alignment.
- Future directions
  - Account for risk and adjust SDRs—climate beta
  - Future climate change may lower equilibrium interest rates further. Deeper understanding requires joint modeling of macro-finance trends, the economy and the climate system.

# Alternative $r_t^*$ estimates from one-year yield

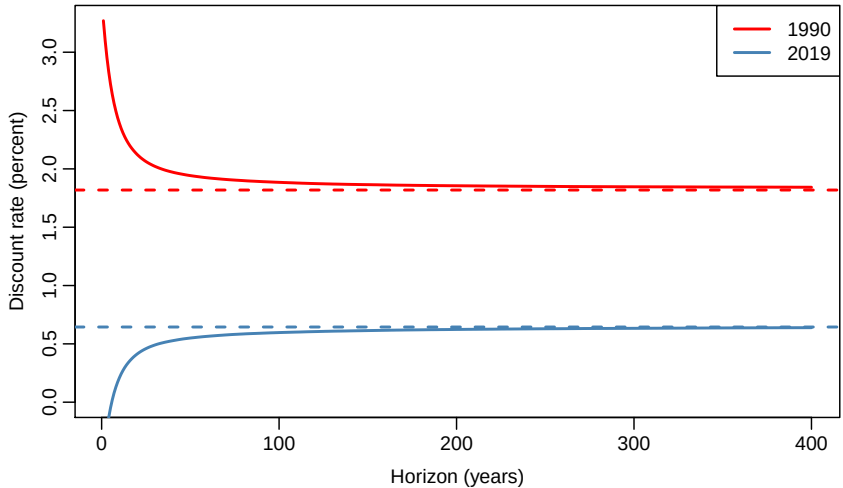


# Alternative $r_t^*$ estimates from ten-year yield

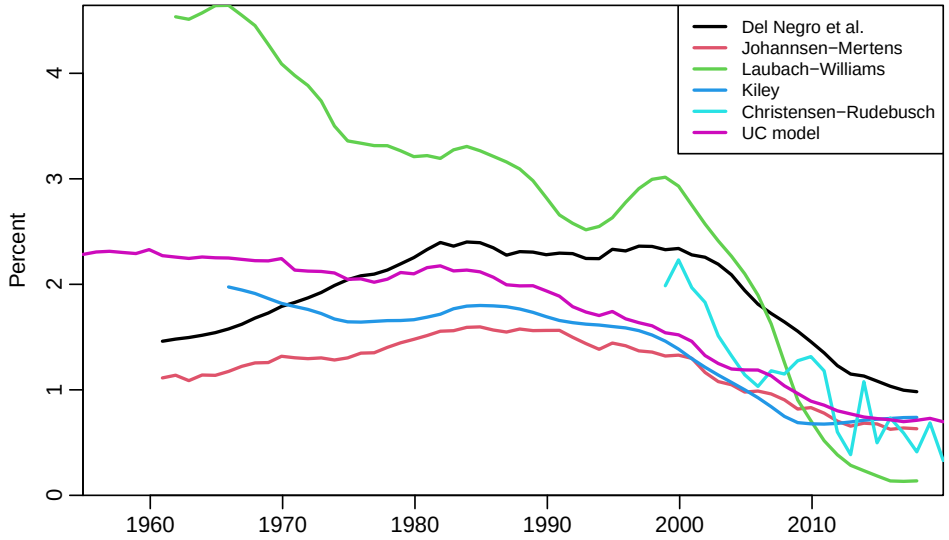


# Term structure of SDRs without convexity

Long rates as averages of expected future short rates
(UC model for 1y real Treasury yield)



# Macro-finance estimates show secular decline in $r_t^*$



# Updated Christensen-Rudebusch estimate of $r_t^*$